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Towards solar cells with black silicon texturing passivated by a-Si:H

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***Abstract* — We introduce surfaces of black silicon (bSi) fabricated by reactive ion etch (RIE) and passivated by hydrogenated amorphous silicon (a-Si:H). We demonstrate minority effective lifetime over 1.5 ms for the best bSi surfaces, corresponding to over 700 mV of implied open circuit voltage, values higher than on reference surfaces prepared by KOH etching. Fabrication of solar cells resulted in promising efficiency of 16.1 % for bSi as compared to 18.5 % for KOH references. Quantum efficiency measurements revealed that the bSi cells lose approximately 0.5 mA cm^{-2} of current density in the visible and of 0.8-1 mA cm^{-2} in the infrared (IR) region. Current work is ongoing to further reduce surface damage during RIE to maximize the open circuit voltage and to optimize the deposition of a-Si:H on our bSi in order to reduce the loss in current density.**

***Index Terms* — silicon heterojunction, a-Si:H, black silicon.**

I. Introduction

Black silicon (hereinafter bSi) [1,2] has demonstrated great potential as texturing method Si photovoltaics thanks to its excellent intrinsic antireflective properties both at normal and at high incidence angles [3]. Power conversion efficiencies between 18 and 22% have been achieved in the lab using laser-doped selective emitters [4], Al_2O_3/SiN_x passivation stacks, [5], and interdigitated back contact (IBC) cells [6]. These results have been obtained using maskless reactive ion etch (RIE) for the Si texturing. The increased surface recombination due to increased surface area and process-induced damage currently limits the open circuit voltage (V_{oc}) and therefore the efficiency of RIE textured solar cells. Hydrogenated amorphous Si (a-Si:H) is an outstanding passivation layer on Si [7] and is the core of the silicon heterojunction solar cell (SHJ) technology that holds the current record for single junction Si solar cell at 26.7% [8]. a-Si:H seems therefore an appropriate candidate to passivate a notoriously challenging surface such as RIE-textured Si. Passivation of bSi fabricated via metal assisted chemical etch using a-Si:H was attempted by Mews *et al.* and showed promising results [9]. Here, we present our first attempt at combining RIE bSi with a-Si:H passivation. We demonstrate excellent lifetime results, with the best bSi wafer showing higher implied V_{oc} (iV_{oc}) than a microstructured surface with pyramids obtained by conventional alkaline texturing. Preliminary results from solar cell fabrication showed lower conversion efficiency for the bSi-based cells as compared to the reference cells. Quantum efficiency measurements give indications on how to improve the efficiency of cells based on a-Si:H/bSi .

II. Methods

4'', 350 µm thick CZ n-type (100) Si were used as substrates. RIE texturing was performed in a SPTS Pegasus system with: process temperature of -20 °C, SF_6 and O_2 plasma with 7:10 gas flow ratio, 38 mTorr chamber pressure, 3000 W coil power, 10 W platen power. The process time was varied between 6 and 30 min. These wafers where then RCA cleaned, without the last HF dip to keep the chemically grown SiO_2 layer on the surface. The pyramid texture, as for the reference, was prepared by KOH based alkali etching at 83 °C for 20 min. The a-Si:H i/p an i/n passivation layers were deposited by plasma enhanced chemical vapor deposition (PECVD) at temperature range of 140–160 °C with SiH_4, H_2 gas for intrinsic and also B_2H_6 and PH_3 gas for p- and n-doped layer. Scanning electron microscopy was performed in a SEM (Hitachi S-4300) at an accelerating voltage of 10 kV. Minority carrier lifetime was measured using the quasi-steady state photoconductance (QSSPC) method with a Sinton WCT120TS instrument. The lifetime shown in this study was obtained for the sample with both the front and rear surface passivated with only i a-Si:H layer. Prior to fabrication of solar cells, the Si substrates were cleaned according to [10]. The cell structure was the following: Ag-grid / ITO (75 nm) / p a-Si:H (5 nm) / i a-Si:H (10 nm) / n c-Si substrate (350 µm) / i a-Si:H (10 nm) / n a-Si:H (7 nm) / ITO / Ag. The cell designated area was 1.045 cm^2, including the Ag grid. The performance (V_{oc}, J_{sc}, *FF*) was characterized by the current-voltage (*J-V*) measurements at a standard condition (AM1.5 1-Sun at 25 °C). The external quantum efficiency spectra were measured under white light bias.

III. Results

Fig.1 shows cross-section SEM images of bSi samples with different RIE time, as well as of the KOH textured reference. The surface of the bSi is characterized by hillock-like structure with height and base that generally increase with increasing RIE time. In particular, the height changes from approximately 200 nm for 6 min RIE to more than 1 µm for 30 min RIE.

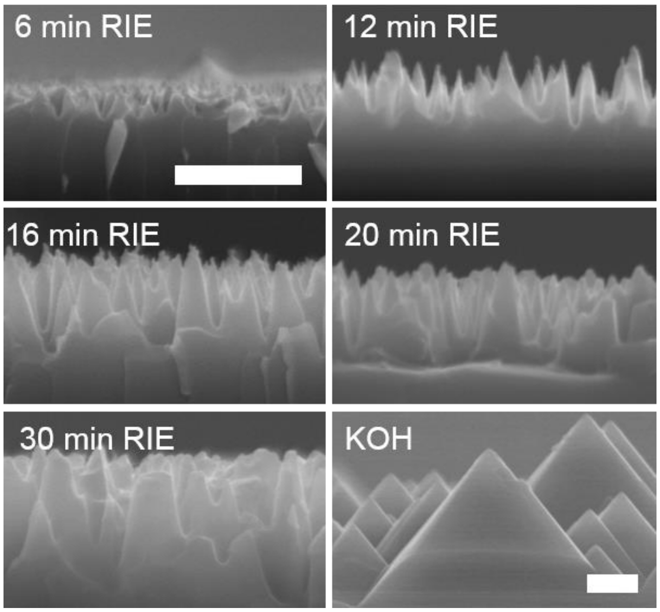


Fig. 1. Cross-section SEM images of Si surfaces textured by RIE and KOH. Both scale bars represent 1 µm.

Measurements of minority carrier effective lifetime τ_{eff} as function of injection level Δn reveal that the quality of passivation by a-Si:H is strongly affected by the RIE time, as shown in Fig. 2(a). For 6 min RIE, τ_{eff} is above the one measured on the KOH textured surface for injection higher than 5×10^{14} cm^{-3} (τ_{eff} = 1.52 ms for 6 min RIE and τ_{eff} = 1.27 for KOH texturing.) τ_{eff} decreases considerably for 12 min RIE, remains approximately the same for 16 min RIE and then drops further for 20 and 30 min RIE. These values translate into iV_{oc} values of 706 and 695 mV, respectively (see Fig. 3(c)). If fully exploited, this would lead to the highest V_{oc} measured on bSi based solar cells. We speculate that the drastic decrease in τ_{eff} for RIE time of 12 min and longer may be due to less-completed surface coverage of the i/p and i/n a-Si:H passivation layer, which is currently under investigation.

Solar cells were fabricated from the 6 min RIE wafers as well as from the KOH textured wafers as reference. Results are summarized in Fig. 3. It is clear from the *J-V* curves (top panel) that the KOH textured cells average performance is higher than that of the bSi cells. The KOH textured cells display a higher J_{sc} by 1.33 mA cm^{-2}, a higher V_{oc} by 16 mV, and a higher fill factor (FF) by 5.9%, resulting in a 2.4% higher efficiency (18.5 against 16.1%). We note that there is quite some room for improvement as the results presented here are from our first

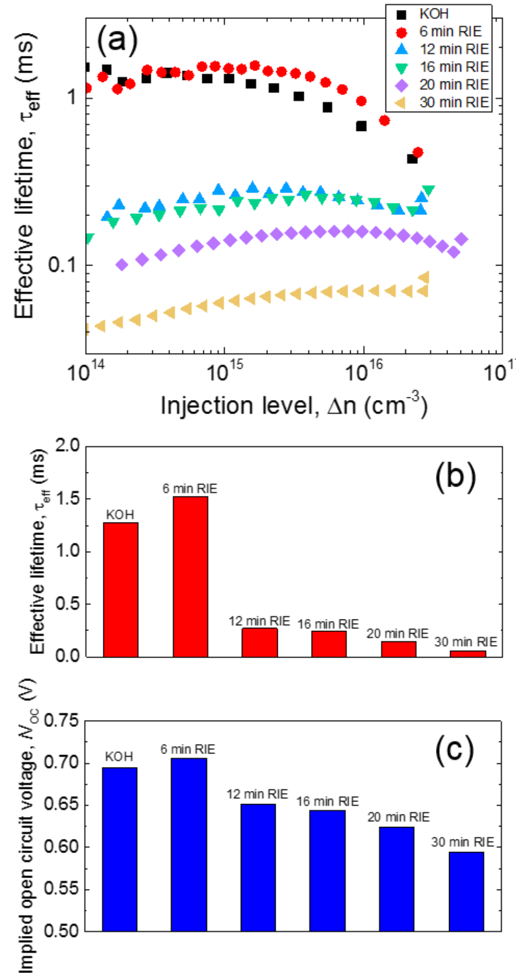
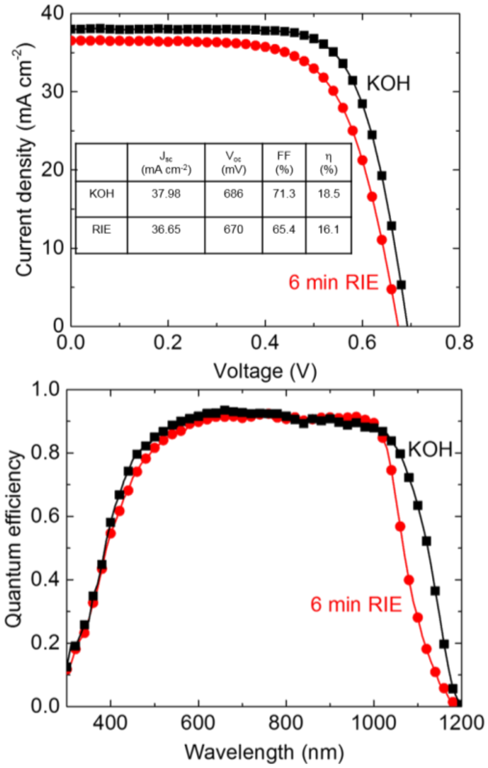


Fig. 2. Summary of lifetime measurements. (a) Effective lifetime as function of injection level. (b) Effective lifetime measured at injection level of 10^{15} cm^{-3}. (c) Implied open circuit voltage calculated at injection level of 10^{15} cm^{-3}.

batch of cells. The trend between iV_{oc} and V_{oc} is reversed: the net loss going from lifetime samples to full solar cells is of 27 mV when replacing KOH texturing with RIE. Possible reasons for this may include ITO sputtering damage to bSi and a higher shunt resistance caused by non-optimal contact between bSi and ITO. Poor contacting could also explain the rather large difference in *FF* is rather large between these samples. There are two spectral regions where the KOH cells perform better than the RIE cells (see bottom panel of Fig.3), in the visible (400-700 nm) and close to the bandgap of Si (1000-1200 nm). By spectral weighted integration of the QE curves, we concluded that the loss in J_{sc} for the RIE cells is of 0.5 mA cm^{-2} in the visible and of 0.8-1 mA cm^{-2} in the IR. Interestingly, Mews *et al.* reported a higher J_{sc} loss in the visible and a lower loss in the IR as compared to our results, which may be connected to difference in the characteristic shape and size of bSi. In our case, the loss in the IR is due to poor light trapping of the bSi caused by the relatively small characteristic size and by the shape of the nanostructures, as discussed in [11]. While



	J_{sc} (mA cm^{-2})	V_{oc} (mV)	FF (%)	η (%)
KOH	37.98	686	71.3	18.5
RIE	36.65	670	65.4	16.1

Fig. 3. Top: Averaged J-V curves for 6 min RIE textured cells and for KOH textured reference cells. Bottom: quantum efficiency measurements

texturing both sides of the cell might ameliorate this issue, further work on the RIE is needed to produce structures with more appropriate shape and even lower additional surface damage. It is difficult to determine the cause of loss in the visible from the data presented here, nonetheless we speculate that this could be due to enhances parasitic absorption in the a-Si:H as compared to the KOH textured cells. Since the bSi nanostructures are more convex than the pyramids, the effective thickness of incoming photons in the bSi textured surface could be higher.

IV. Conclusions

We presented a combination of black silicon fabricated by RIE and a-Si:H films for surface passivation. We measured minority effective lifetime exceeding 1.5 ms for the best bSi surface, corresponding to over 700 mV of implied open circuit voltage, a higher value than a reference KOH textured wafers. Fabrication of solar cells resulted in promising efficiency of 16.1 % for bSi as compared to 18.5 % for KOH references. Quantum efficiency measurements revealed that the bSi cells lose approximately 0.5 mA cm^{-2} of current density in the visible and of 0.8-1 mA cm^{-2} in the IR. Current work focuses on further reducing surface damage during RIE and on optimizing the deposition of a-Si:H on the bSi. In addition, the efficiency is likely to be increased by resorting to substrates with better bulk quality.

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